PULSED POWER FOR FUTURE LINEAR ACCELERATORS

Peter D. Pearce

High-energy accelerators

High-energy accelerators enable us to collide particle beams together and create conditions believed to be similar to those existing during the first moments of our universe about 15 billion years ago. These accelerators and their accompanying detectors are the light sources and microscopes used to look at the elementary particles. Colliders are machines that accelerate and guide oppositely directed, and tightly focused beams of particles into collision at the intersection point where enormous amounts of energy are released.

Three types of high-energy collider machines are being studied by physics laboratories and collaborations worldwide [1]. These studies cover linear e^+e^- colliders [2], muon colliders and circular hadron colliders [3]. Table 1 below shows some parameters relevant to the design of pulsed power systems for e^+e^- linear colliders with a centre-of-mass energy of 1TeV. Variants of these accelerator parameter sets are also being defined for colliding beam energies in the range 0.5 to 5 TeV.

		TESLA	**JLC(C)**	**ILC-NLC(X)**	**CLIC**
Main linac RF frequency	GHz	1.3	5.7	11.4	30
Beam collision energy	TeV	0.8	1.0	1.0	1.0
Accelerator structure		Superconducting	Normal conducting	Normal conducting	Normal conducting
Acceleration gradient (loaded)	MV/m	34	47	55	100
Linac repetition rate	Hz	5	50	120	150
Number of klystrons		1232	5864	6624	200
Number of modulators		1232	5864	3312	200
Klystron peak power	MW	8	100	75	50
RF pulse width	μs	1300	2.4	1.55	50
AC power to make RF	MW	132	133	167	102

Table 1 Some representative e^+e^- collider parameters

Although each of these studies aims towards a high-energy collider, a number of different main linear accelerator technologies are being used. The difference between these new collider schemes and existing machines is the very large amounts of RF power that has to be generated, and therefore the necessary R&D programmes to make them <u>power efficient</u>, <u>cost effective</u>, <u>reliable</u> and <u>compact</u>. Superconductivity also has an important role for some machines to reduce energy losses. Others use extremely high radio frequencies to obtain very high field gradients in the acceleration cavities. Nevertheless, most accelerators do have some technology in common [4]. Pulsed power in an accelerator complex is associated with many sub-systems that assure an efficient acceleration and transfer of the particle beam from creation at the source, to its required destination. This paper reviews some of the pulsed power klystron-modulator systems exploited for the generation of RF power in the e^+e^- linear colliders of Table 1.

System design criteria

There are a number of challenging and large e^+e^- accelerator schemes being studied theoretically, and experimentally using dedicated test facilities, in several laboratories. Each of the schemes require large numbers of pulsed power sub-systems such as fast beam kickers, pulsed septum magnets, and most importantly, klystron-modulators to provide RF accelerating power. The question of what design criteria have to be addressed for these new schemes is an important issue, particularly when the sub-systems required are numbered in thousands. These sub-systems are also distributed over many kilometres in the collider, therefore requiring time (Figure 1) to detect, locate and make any repair or correction to faulty equipment. Down time affects the productive capability of accelerator systems, by reducing beam quality, increasing operating costs and causing major perturbations for the experimental programmes. The large number of components and sub-systems required for future schemes brings home the point of designing in reliability and maintainability from the start. The cost of specifying, designing and building reliable systems is not more than the cost of an unreliable system and, in the long term, must be considerably less. Even with the best possible design however some faults and down time will always occur.

Peter D. Pearce is with the PS Division, CERN, Geneva, Switzerland.

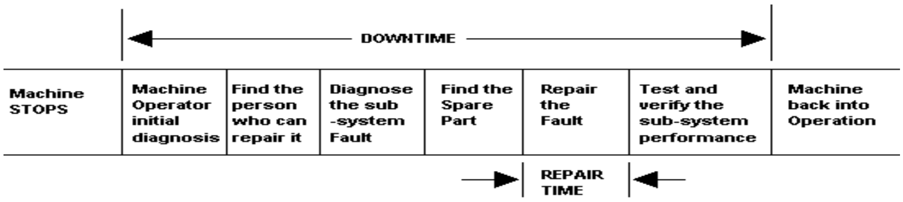


Figure 1 Accelerator down time components

Effort is then required to ensure that these large arrays of sub-systems are equipped with computer linked, smart diagnostic tools [5], to give assistance for a rapid recovery from fault situations. Below in Table 2 are some criteria that can be applied to the design of high-power klystron-modulators for use in large accelerator schemes.

Sub-systems	Remarks
Cost	Many sub-systems to be installed, so apply cost effective engineering methods
Efficiency	Efficient conversion of AC wallplug power to RF power for lower running costs
Size	Reduce unit size for easy handling, location on accelerator, and less building space
Reliability	Conservatively rated components with long lifetime design + high target MTBF rates
Maintainability	Diagnostic methods, modular construction, fast replacement with off-line repair
Performance	Choice of technology/operating parameters for desired performance and availability

Table 2 Design criteria of large systems

Klystron-Modulator technology

An important focal point for pulsed power over the next few years will be the design and development of adequate modulators for driving the new high-power klystrons, to be used in the linear collider research and development programmes, and eventually to be used in a final scheme. A modulator is often one of the most expensive parts in the RF system of an accelerator, and at the same time can cause the most downtime if not designed with care. The present status of the klystron-modulators for the future linear collider schemes given in Table 1 are reviewed below and the different technology developments and requirements have been identified and summarized.

a) TESLA

The TESLA linear collider scheme (TeV Energy Superconducting Linear Accelerator) is being studied by a international collaboration between the DESY laboratory, Hamburg, Germany and several other high energy physics laboratories and universities. The pulsed power specification of the TESLA machine requires each klystron-modulator to produce an RF pulse of 10MW peak power, at a repetition rate of 10Hz. A total of 1232 modulators are required with the parameters given below.

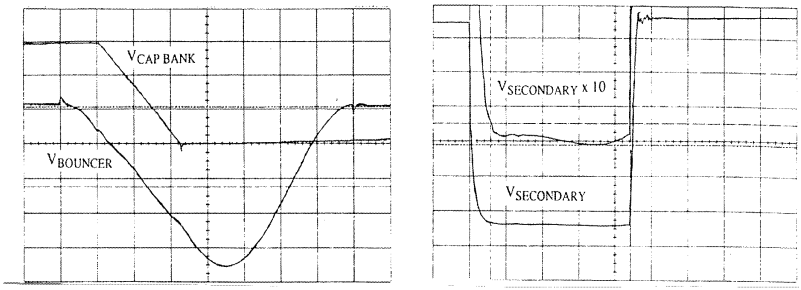
Pulse width (99%) ms	Klystron beam voltage kV	Flat top variation %	Klystron beam current A	Repetition rate Hz
1.5 to 2.0	130	1	130	10

The unusual parameter is a flat top pulse width of 1.3 ms. The total pulse width including the rise time is around 1.5 ms. Amplitude fluctuations during the long flat top are required to be $\leq \pm 1\%$, since any variations of the pulsed klystron voltage cause an unwanted energy spread in the accelerated particle beam. This stability and the long pulse requirement then leads to several interesting modulator designs being investigated.

1. Line type modulator with pulse forming network (PFN) and pulse transformer (PTx)
2. Switched capacitor bank modulator with “bouncer” droop compensation circuit
3. Superconducting magnetic energy storage (SMES) modulator

The first method is used in many existing klystron-modulator systems (SLAC for example), where pulse lengths from a few µs up to some tens of µs only are needed. However, with a pulse of 1.5 ms the design becomes very bulky, with the need to use iron cored inductors because of the long electrical length and the desire to keep the assembly small. The design of a 24 section PFN with 8.3 Ω impedance, and 2 m wide x 4 m long x 2 m high, meeting the specifications was made. An evaluation of the PFN costs of this type of modulator was made, and the results prompted a search for other solutions.

The switched capacitor bank solution with droop compensation [6] in Figure 3 reduces cost and physical size of the modulator. A small value capacitor bank allows a discharge of about 20% during the pulse. This droop is compensated for with a bouncer LC circuit that creates a single sine wave (period about 7 ms) keeping the output voltage constant. This technique reduces the stored energy considerably. The capacitor bank is connected to the primary high side of the pulse transformer and the compensating bouncer circuit is connected to the primary low side. The impedance of this bouncer circuit is made small with respect to the referred impedance of the klystron load. The operating sequence is to first start the compensating circuit, and then close the main switch connecting the capacitor bank to the pulse transformer. The main switch is opened at the end of the pulse, and the compensation circuit recharges to its initial voltage level. The pulse is flat to approximately 1% over the desired 1.3ms duration and has been tested with a pulse width flat top of 2.0 ms at the operational voltage. In Figure 2 (a) the main capacitor bank voltage has the zero point suppressed, and in (b) the expanded zero has also been suppressed.



(a) (b)

Figure 2.

(a) Main capacitor bank voltage (top) and bouncer voltage 500V/div, 1ms/div. (bottom)

(b) Expanded secondary voltage (top) and secondary voltage 20kV/div, 0.5ms/div (bottom)

The circuit protects the semi-conductor switches and klystron from voltage breakdowns by using an inverse diode undershoot network on the transformer primary and a high speed ignitron crowbar system before the main GTO switch.

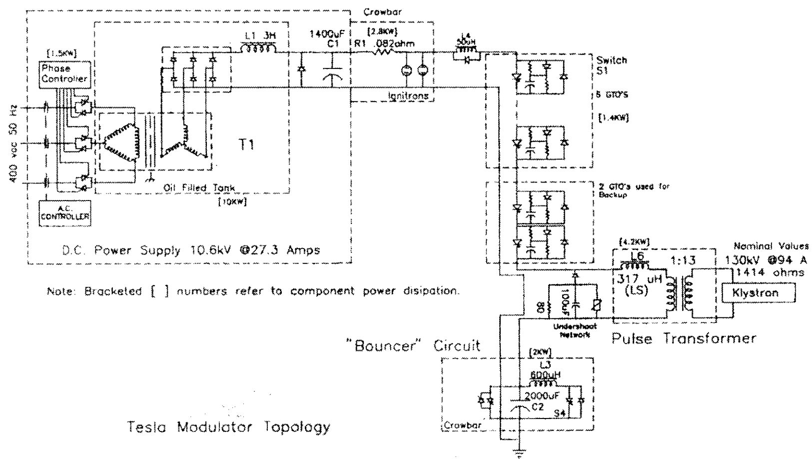


Figure 3 Basic switched capacitor modulator circuit

A superconducting magnetic energy storage modulator (SMES) is also being studied as an alternative modulator system. Storing energy inductively is very attractive since in terms of the energy density, inductive storage systems are more efficient than capacitive ones due to the relatively large space required for a capacitor bank. The energy density of a magnetic field can be made greater than that of an electrostatic field, allowing magnetic energy storage to be made in a smaller volume. However, the specification for the opening switches in an inductive system is considerably more stringent than that for a closing switch in a capacitive system. The operating parameters for a 25 MW SMES modulator are very similar to the other modulators above. Research and development into this energy storage method is continuing.

b) JLC(C)

The development of the Japanese Linear Collider (JLC) C-band modulator in KEK, Japan, is based on the reliability criteria mentioned earlier. The KEK C-band modulator [7] in Figure 4 is a standard line-type design with a thyratron main switch for discharging the PFN, but uses direct HV charging of the PFN with a commercially made, compact, switched mode inverter high voltage power unit. The operating parameters from tests made with the prototype unit of the C-band klystron-modulator are given below. A total of 5864 modulators will be needed.

PFN voltage kV	Klystron voltage kV	Klystron current A	Klystron power MW	Repetition rate Hz	Voltage pulse width μs	Rise/Fall times μs	RF pulse width μs
48	348	296	50	100	4.35	0.8/1.9	2.5

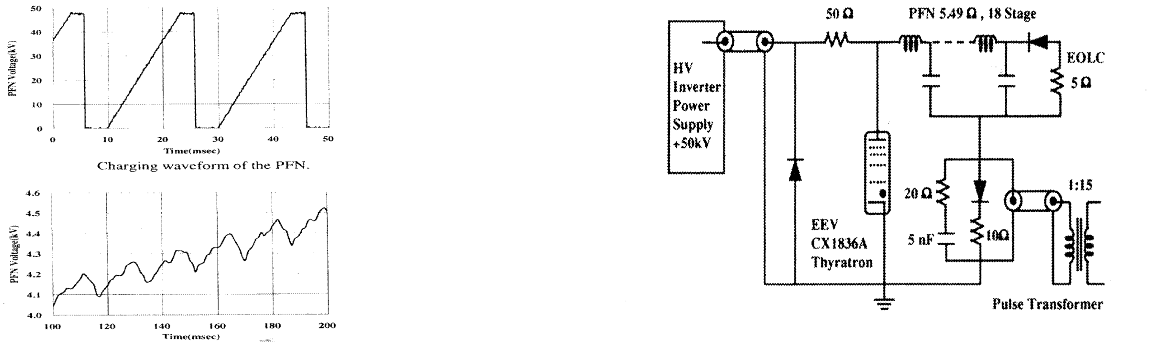


Figure 4 The basic circuit of the C-band modulator and charging waveforms

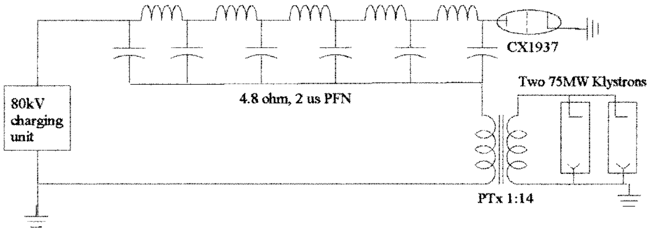
The switching power units above are widely used in power electronics with proven reliability, high efficiency, extremely low stored energy and are capable of high charging rates (>30kJ/s) at high voltage. This is in part due to the progress made with Insulated Gate Bipolar Transistors (IGBT's). The switching frequencies used are around 50 kHz allowing the size of the internal high voltage transformer to be greatly reduced, giving a compact assembly. In this application, the PFN is charged with a ±0.1% pulse to pulse voltage stability, eliminating the traditional and energy wasteful d'Qing circuit found in older systems. Reduction of electro-magnetic (EM) noise due to thyratron switching was seen as an important issue for the KEK modulator. This noise can often dominate the spectrum of electronic noise in an accelerator making problems for control systems and feedback networks. With thousands of thyratrons switching in synchronism this could create a very serious stability problem, and also an expensive screening cost for other systems. As well as using a screened cage, a low-impedance earth return plane is connected from the thyratron, to the PFN, the pulse output cable screen, the pulse transformer and klystron to reduce the EM noise. A prototype modulator was tested with a new 5.7 GHz C-band klystron and a RF pulse width of 2.5 μs, and a flatness of ±0.5% obtained. The rise and fall times of the modulator voltage pulse were 0.8 and 1.9 μs respectively. The measured pulse efficiency reported was about 56%, which is less than is required to keep running costs low and wall-plug power below 200 MW for a 0.5 TeV collider scheme.

c) ILC-NLC(X)

The International Linear Collider collaboration was set up early in 1998 for the optimisation of an X-band collider machine. The design is centered on work being done at the Stanford Linear Accelerator Laboratory (SLAC) in California and at KEK in Japan. The study is based on proven technology that uses room temperature, travelling wave copper accelerating structures. These are designed for the X-band frequency of 11.4 GHz, rather than the S-band 3 GHz frequency found in most of today's linear accelerators. The 75 MW X-band klystrons, developed at SLAC for the Next Linear Collider (NLC), currently have a pulse width of about 1 μs and are being developed for a required pulse width of 1.5 μs at 75 MW. These new devices will have permanent magnet focusing systems instead of a power consuming solenoid to improve overall power efficiency. The X-band baseline modulator parameters currently being used [8] are shown below.

PFN voltage kV	Klystron voltage kV	Klystron current A	Klystron power MW	Repetition rate Hz	Voltage pulse width μs	Rise time μs	RF pulse width μs
80 (max)	500	530	75	120	2.5	0.3	1.5

The baseline design of the NLC modulator uses a conventional topology (Figure 5). However, it drives two X-band klystrons from the one pulse transformer to give both economic and configuration advantages, since the modulator design is an integral part of the linear accelerator tunnel design. The development programme is to improve the power efficiency, operational reliability and performance, whilst keeping the projected manufacturing costs down for the 3312 modulators needed. The areas being investigated include low-loss energy storage (PFN) components, rise time and pulse shape of the voltage pulse (pulse transformer), and the thyratron switch design for very high (50,000 hours) operation.



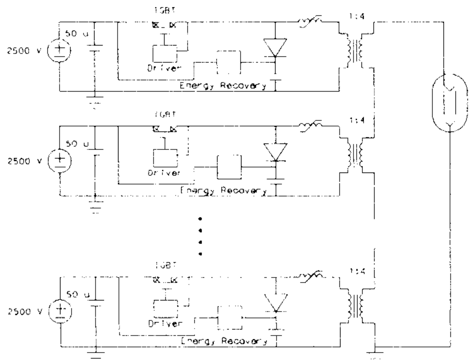


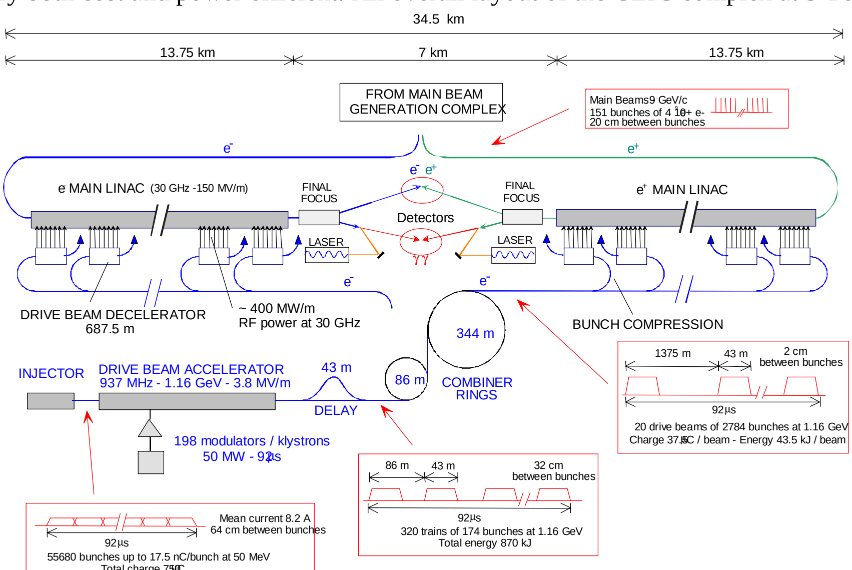
Figure 5 Baseline NLC modulator

Figure 6 NLC solid state modulator

A solid state modulator [9] is also being investigated as in Figure 6. This modulator has multiple parallel IGBT's each driving a separate transformer primary winding on the pulse transformer. Each IGBT switch operates at 2500 V into a 1:4 ratio step-up transformer. A klystron voltage of 500 kV is obtained from adding the secondary winding voltages in series. To improve rise time, a 1:1 turns-ratio with one hundred IGBT's at 5kV will be assessed for driving 8 X-band klystrons. These designs eliminate the thyratron switch and the PFN network and hold a promise of higher power efficiency, but also entail some risks with the technology. Development of these modulators is continuing and cost models are being derived.

d) CLIC

The Compact LInear Collider (CLIC) study [10] at CERN, Geneva is based on a new approach of Two-Beam Acceleration (TBA). The large amount of RF power (400 MW/m) required to generate the high accelerating fields (150 MV/m) in specially damped 30 GHz normal-conducting accelerating structures, is provided by a novel RF power generating scheme which is potentially both cost and power efficient. An overall layout of the CLIC complex at 3 TeV is shown in Figure 7.



OVERALL LAYOUT OF THE CLIC COMPLEX AT 3 TeV C.M.

Figure 7

The RF energy is initially stored in a long-pulse electron beam (~100 μs), which is efficiently accelerated to about 1.2 GeV by a fully-loaded, normal-conducting, drive beam linear accelerator operating at 937 MHz. This long beam pulse is then compressed into segments using combiner rings to create a sequence of 20 higher peak power drive beams with gaps in between. This train of drive beams is distributed from the end of the linear accelerator against the main beam direction down a common transport line so that each drive beam can power a section of the main accelerator. After a 180-degree turn, each high-current, low-energy drive beam is decelerated in low impedance decelerator structures, and the resulting power is used to accelerate the low-current, high-energy beam in the main linear accelerator.

There are 198 conventional line-type, long-pulse multi-beam klystron-modulators used for creating the pulsed power for each drive beam accelerator in the 3 TeV design. The multi-beam klystron (MBK) has been chosen for its high electronic efficiency (~70%), wide bandwidth, and lower operating beam voltage. The parameters being used for the baseline design of the 50 MW peak power, klystron-modulators are shown below (for the 3 TeV collider case), using a six-beam MBK.

PFN voltage kV	Klystron voltage kV	Klystron current A	Klystron power MW	Repetition rate Hz	Voltage pulse flat top μs	Rise time μs	RF pulse width μs
50 (max)	230	333	50	75	100	7.5	93

The baseline modulator configuration [11] is very similar to that of Figure 5, except that only one 50 MW klystron is driven from each modulator, and the PFN voltage has a target value of 50 kV(max). This voltage level is chosen to avoid using large quantities of insulating mineral oil for each PFN and thyratron switch. The development of the MBK will most likely start with a tube design at a lower peak power and, at this stage, it is possible that two lower power klystrons could be connected up to a single modulator. The high voltage PFN capacitor charging system will use switched-mode power units, as in the JLC C-band design, for improving the power conversion efficiency and reducing the physical size of each installation. The 50 MW peak power klystron-modulator design [12] needs a high voltage charging system of about 800 kW, so that a modular scheme of several lower power units may be used, which could also allow redundancy or a gradual degradation within each system under fault conditions. Each of the 99 accelerating cavities in a single drive beam accelerator is driven from a RF klystron-modulator assembly as shown in Figure 8.

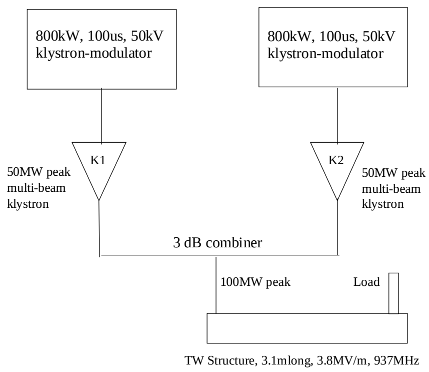


Figure 8 Klystron-modulator drive scheme

An alternative modulator design is also being investigated that uses a storage capacitor and a solid state switching device to replace the PFN and thyratron switch components. A switched-mode power unit charges up the storage capacitor, which is subsequently switched into the pulse transformer and klystron load by an array of solid-state switches. The pulse width being generated is determined by the ON time of the series switch array. A droop compensation method will have to be used to maintain the 1% flat top specification. A small number of similar solid-state systems [12] are currently being installed in accelerators for driving klystrons with 100 kV, 150 A pulses directly without the pulse transformer. Their long-term reliability and development is being followed closely.

Klystron-modulator efficiency

A key consideration for the acceptability of any collider design is the efficiency with which AC line power is converted into RF power for accelerating the particle beams. Pulsed power klystron-modulators are major contributors to this overall efficiency requirement. Therefore each element of a modulator has to be analysed in this aspect in addition to its dynamic and reliability performance. Klystrons that have periodic permanent magnet (PPM) focusing systems will obviously have an efficiency advantage over those with solenoidal focusing which can consume a significant percentage of the klystrons average power. A block diagram of the major functional parts that influence the performance and efficiency of the baseline klystron-modulator are given below.

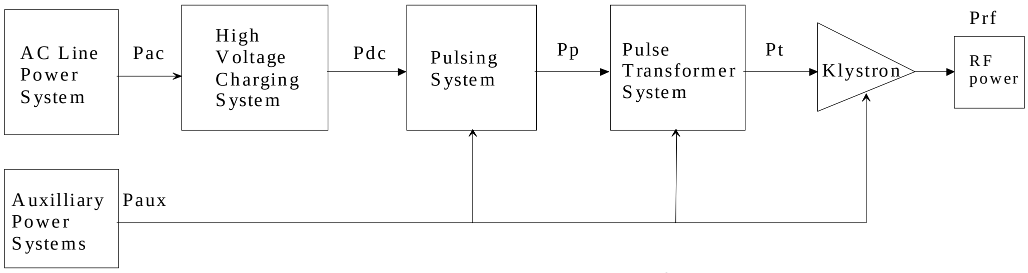


Figure 9. Baseline klystron-modulator functional parts

From this diagram the overall klystron-modulator power efficiency can be written as: $\eta_{km} = Prf/(Pac+Paux)$. The projected or extrapolated system efficiencies for the CLIC long-pulse klystron modulator with solenoidal focusing are in Table 3.

System	Parameters	Efficiency symbols	Assumed efficiency %	Target Efficiency %
Charging system	AC line to DC high voltage	$\eta_c = Pdc/Pac$	92	96
Pulsing system	PFN and thyratron efficiency	$\eta_p = Pp/Pdc$	99	99
Pulse transformer	Tx & energy transfer efficiency	$\eta_t = Pt/Pp$	95	97
Klystron	Electronic efficiency	$\eta_k = Prf/Pt$	65	70
Klystron-modulator	AC to RF efficiency	$\eta_{rf} = Prf/Pac$	56	65
Klystron-modulator	Total Single system efficiency	$\eta_{km} = Prf/(Pac+Paux)$	55	64

Table 3 Klystron-modulator efficiency components

Klystron-modulator component development

a) High-voltage charging

High-voltage charging with switch-mode power converters has an advantage that the stored high-voltage energy is very small, compared to transformer-multi-phase rectifier systems commutated by the line frequency. Advances in the design of power electronic components now enable the production of 100 kW units and more, operating at frequencies up to ~50 kHz and having conversion efficiencies between 90 and 95%. However, the design of units in this power class have to ensure a low level of EMI being generated with a very low order of current harmonics being injected back onto the AC mains, while running at close to unity power factor. Because of the higher operating frequency the resulting design is very compact and the high efficiency is very attractive with respect to running costs. All collider schemes are looking at various methods to generate pulsed high voltage energy efficiently, and the high power switch-mode converters are a very important step in this direction. Development of these units to perform at high power is actively continuing, with some manufacturers driven perhaps by the accelerator requirements, and which will be a necessary component in the future for large systems.

b) Energy storage

Most klystron-modulators use a PFN lumped component network for defining the voltage pulse width, except Tesla, who in the present configuration have a storage capacitor with droop compensation and a GTO switch assembly. To match the referred klystron load impedance (in some cases two klystrons in parallel) through the step-up pulse transformer, more than one PFN is put in parallel (NLC) in the standard line type modulator. The coils of each cell are made adjustable and with mutual inductance coupling, to produce an acceptable (~1%) flat top pulse. The energy storage capacitors in the PFN have some internal inductance, which has an impact on the pulse shape and also limits the rate of rise of current. At the present, oil filled, film capacitors (traditionally used) are still a reliable choice, with proven long life times ($>10^{10}$ discharges) although most have internal inductance values around 140 nH causing an energy loss during the rise time of the pulse. Glass solid dielectric capacitors have been tested at SLAC and elsewhere which have a much lower inductance (30 nH) but also have a large energy loss, which is a function of temperature.

c) Energy switching

At present thyratrons remain the best switch option for almost all modulator designs and are ideally suited for discharging energy stored in capacitor banks or PFN's into klystron loads. Because the device uses a gas discharge for current conduction, it is robust and very fault tolerant where conditions can exceed the normal operating ratings. For the long pulse, high repetition rate modulator of the CLIC drive beam, the average current is high (~ 30 A) at the proposed PFN charging voltage. Thyratron lifetimes appear to decrease as the average current increases. Two thyratrons however, can be used in parallel in this situation, or the charging voltage specification increased beyond the 50 kV limit. This solution puts up the cost or increases the high voltage insulation requirement and may affect reliability. For linear colliders having very large numbers of thyratrons (or other switches) the actual lifetime obtained is an important parameter. Additionally, the requirement to "range" the internal gas pressure via the reservoir voltage for certain thyratron types is a very time consuming task in a large installation. At least one manufacturer makes a number of tubes that are internally gas pressure compensated that remove this problem over the average lifetime. An alternative switch solution for use in the modulator is the GTO, as in the low-voltage, low-repetition rate design for Tesla, or an array of IGBT devices as a solid-state switch. In order to use IGBTs for high-voltage switching, many devices must be cascaded in series. However, to increase the power handling capacity of such an assembly, several of these series chains must operate in parallel, and these design requirements also provide a degree of flexibility and modularity over a large power range. Nevertheless, a very good method of protection is required to ensure that the load power is shared equally between devices, and that no single device sees harmful or destructive voltages. Until recently, few commercial or laboratory-built systems existed using these device-arrays as the principle method of pulsing klystrons. Development of these devices continues to advance at a rapid rate, and a number of users will soon be able to provide some of the answers to the long-term reliability question.

d) Pulse transformer design

Pulse transformers are an important element in a modulator design and affect the energy transfer efficiency scenario. A direct energy transfer efficiency measurement is the ratio of the useful energy in the flat top portion of the pulse with respect to the total pulse energy, including the rise and fall time portions. This is usually written as $\eta_E \cong T_p/(T_p+\alpha T_r)$ where T_p is the flat top pulse width, and T_r the rise time. The factor α depends on the rise and fall times and pulse shape. This energy transfer efficiency from PFN to klystron load is mainly determined by the pulse transformer design, and in particular the effect of leakage inductance L_L and stray capacitance C_D on the pulse rise and fall times. The klystron capacitance seen at its cathode adds to the transformer stray capacitance $C_T = C_D + C_K$. The pulse rise time at the transformer is limited by the resonant period $T_R \sim \pi(L_L C_T)^{1/2}$, and since L_L is proportional to n^2 the rise time is proportional to n, the turns ratio. A low transformer turns ratio gives a faster rise time but implies a higher voltage on the PFN, which also has to be held-off by the thyratron switch and other components. Energy transfer efficiency is very important for the JLC and NLC modulators where the flat top pulse widths are only 1 to 3 μs and the pulse rise times are 0.3 to 0.8 μs. The Tesla and CLIC modulator pulse widths are in the hundreds of microseconds, so that rise time (150 and 7.5 μs respectively) becomes a very small percentage of the total pulse width, giving a higher energy transfer efficiency. However, long pulse widths exhibit more flat top droop, which has to be compensated for by methods such as using a tapered impedance PFN or the Tesla bouncer technique. Finally the pulse transformer has to match the klystron load with the PFN impedance to obtain optimum power transfer conditions, and therefore its design is generally a compromise. An interesting fast rise and fall time (20-50 ns) pulse transformer can be made [15] using coaxial lines (transmission line transformer), but its physical size and limited voltage hold-off per "turn" exclude it in its present state of development for high power klystron-modulator operation.

e) Klystrons

All of the proposed linear collider schemes are based on the production and manipulation of RF power in the frequency range from about 1 to 30 GHz. The klystron is used as the primary source of this RF power, including the CLIC two-beam accelerator scheme, for its 937 MHz drive beam accelerator. It is seen that as frequency increases the maximum output available from a klystron tends to decrease [14], so that schemes like the ILC/NLC and JLC resort to using high power pulse compression methods to enhance the peak output power, which does increase the power losses. A maximum klystron efficiency is obtained when the beam voltage is at a maximum and the beam current at a minimum, for a given output power, since the space charge forces in the klystron beam counteract the beam bunching efficiency. These forces tend to blow apart the well defined electron bunches that are needed for high output efficiency. The strength of the CLIC scheme is that the long beam pulse energy is created at 937 MHz, and transported through a series of combiner rings, being converted into a periodic sequence of short, high power pulses at 30 GHz for the main collider accelerator. The other schemes have to create the RF power pulses at the frequency of their main accelerators by directly using klystrons and pulse compressors. Since the maximum field gradients obtainable in the accelerating cavities (before the dark current capture threshold) is known to be a function of frequency ($G_{th} \sim 5.f_{GHz}$ in MV/m), then working at higher frequencies will give a higher beam energy gain per metre, resulting in a shorter accelerator for a given collision energy. For lower frequency, long pulse and cw klystrons, simulations and measurements (SLAC) show that klystron efficiency versus microperveance function can be written as $\eta_{kly} \cong 0.8 - 0.15$ Kμ. The CLIC and Tesla schemes use pulsed multi-beam klystrons as the prime RF power source. The MBK has a lower microperveance per beam (0.5 compared to 1 or 2 for X and C band tubes) and consequently a prospective higher electron efficiency (~70%). However long-pulse, high power (25 to 50 MW) multi-beam klystrons are just being designed and developed, whereas the short pulse 75 MW X-band single-beam klystron is currently being tested and evaluated in a test accelerator facility. The Tesla MBK has already been manufactured and tested on the factory test modulator at the full 10 MW peak power and 65% efficiency, but only with about half its required operating pulse width.

Summary

The present and planned accelerators (LEP and LHC at CERN, or SLC at SLAC for example) will most probably have fulfilled their design goals as research tools by the first part of the next century. New machines with even higher energies and luminosities will be needed for continuing this research in experimental high-energy physics. These future accelerators will be colliding beam machines that will enable the energy frontier to be extended beyond that currently obtained and will rely very heavily on pulsed power systems for the large amounts of RF power that have to be used. There are at least five major areas of sub-system development being addressed for the klystron-modulators of these future linear collider schemes. All focus on the six design criteria given previously, and shown below. The crosses in the table were taken by the author to indicate the most "important" requirement of that sub-system component, although all are important if the designs are to succeed.

	HV Charging	PFN capacitors	High voltage switch	Pulse transformer	Klystron
Cost	x	x	x	x	x
Efficiency	x	x	x	x	x
Size	x	x		x	
Reliability	x	x	x		x
Maintainability	x				
Performance	x	x	x	x	x

The initial costs and running efficiency of a system will certainly determine the budget spending profile of any of the schemes from installation through yearly operation over it's lifetime. Design, development and testing is continuing in all of these areas for application in the klystron-modulators of future high-energy linear accelerators worldwide to make them <u>power efficient</u>, <u>reliable,</u> <u>compact</u>, and <u>cost effective.</u>

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